ENGINEERING CASE LIBRARY

ECL 227

A CEMENT MILL FAILURE

A critical component has failed in the process line of TRUGRIT Cement Company. The failure has threatened to close down operations in the cement plant. Replacement of the failed part may fix the problem, but the costs involved are high and perhaps this "solution" may only cure the symptoms of some more sinister underlying ailment. Is there a permanent solution? Since the plant is insured against equipment breakdown, should the insurance company foot the bill? These are some of the questions facing Andrew Armory, a consultant.

All names are fictitious.

Prepared by Dr. Andrew E. Samuel, Senior Lecturer, Mechanical Engineering, University of Melbourne.

THE CASE OF THE CEMENT MILL FAILURE

OR

WHO IS TO BLAME ?

OR BETTER STILL,

WHO IS TO FIX IT AND HOW ?

A critical component has failed in the process line of TRUGRIT Cement Company. The failure has threatened to close down operations in the cement plant. Replacement of the failed part may fix the problem, but the costs involved are high and perhaps this "solution" may only cure the symptoms of some more sinister underlying ailment. Is there a permanent solution? Since the plant is insured against equipment breakdown, should the insurance company foot the bill? These are some of the questions facing Andrew Amory, a consultant called in by the insurers Australian Sparrow on behalf of their client TRUGRIT Cement Ltd.

Study of the complex thread of interactions in this case is most suitable for courses in Mechanical Engineering. This is not only a cautionary tale for designers and management, but also an interesting engineering detective story.

All names are fictitious.

Prepared by Dr. Andrew E. Samuel
Senior Lecturer Mechanical Engineering
University of Melbourne.

1. THE QUARRY IS SIGHTED (Wednesday, 20th Oct.)

All Wednesdays were alike during term for Andrew Amory, but some were more equal than others. Today was no exception as he sat in his office after lunch struggling through the latest crop of design reports. He was trying hard to concentrate on the work at hand, but the letter from Sparrow kept nudging away at the surface of his consciousness. "If it's so crucial and urgent, why don't they contact me?" Yet there was no mistaking the urgency in Sparrow's letter.

Australian Sparrow
Insurance Co. Ltd.,
134 Burkston Street,
Melbourne, 3000.

14th October, 1975.

Dr. Andrew Amory,
Senior Lecturer,
Melton University,
Parkville Road,
Claytrobe, 3111.

Dear Dr. Amory,

Subject : TRUGRIT Cement Mill Trunnion Failure

As discussed by phone you are to consult with TRUGRIT about causes for their failure. The mill is a 141 Tonne ball mill for raw feed to the cement plant. As it is the only means for producing raw feed it may not be stopped for periods longer than a few days at a time. Even such stoppages could seriously affect production and forward planning. The plant keeps surplus cement in silos with a total capacity of 10,000 Tonne, but the daily production is about 1,000 Tonne. Consequently the matter is serious.

I have already explained your role to TRUGRIT as well as your proposed involvement and they will contact you to make arrangements for any necessary information to be supplied for your investigation. No doubt you will want to visit the TRUGRIT plant to inspect the mill. They will arrange for transport and an escort to the mill.

In anticipation of an early solution
Sincerely,

Adam Jones,
Plant Actuarian.

Amory mused over the whole deal. The letter arrived nearly a week ago. As yet no contact from TRUGRIT. "Ah well", he thought, "perhaps they have gone to another authority for help". In any case it sounded like a run-of-the-mill stressing calculation probably better suited to the temperament of a structures man.

The phone call came in the middle of the afternoon.

"Dr. Amory? - This is Jim Grearson, Australian sales manager for TRUGRIT."

"Yes Jim, Andrew Amory here - I've heard about your problem, but I thought it was urgent."

"We first discovered the cracks in the mill trunnion about a month ago", said Grearson, "and we have kept the cracks under constant surveillance since then." He continued, "as you know we can't stop the mill for any length of time, so we had to find a stop-gap solution."

"Aha, and what did you do?"

"We Metalocked * the cracks and continued to keep a watchful eye on them."

"Isn't that rather dangerous?"

"Not as dangerous as it seems, since the cracks are longitudinal about 250mm long and they have not changed in size since we did the Metal-locking."

"Longitudinal? - Astonishing. Isn't what I expected at all. Don't really know what I expected, but certainly not longitudinal cracks."

"Well", said Grearson, "perhaps you had better come down to the plant. How soon do you think you could make it?"

"What about tomorrow? Could you pick me up at ten?"

"Fine", said Grearson, "our car will be a green Holden No. GKG 486."

Amory knew the drive to Geelong (where the TRUGRIT plant was located) would take about two hours. There would be ample opportunity to question Grearson about the background to the failure. He realised he would need a carefully prepared check-list for the interview, but what should he ask? All he knew was that something had failed, but not the how or when, nor even the specific nature of the equipment that had failed.

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* Metalocking - a mechanical filling and peening method used for crack repairs. Refer to Sketch Exhibit E .

"Wonder what the alternatives are?" - he mused to himself".
"Would there be a need to evaluate a viable alternative?"

He had a private hypothesis about the cause and effect relationships in technical problems. Technical problems are wicked problems in that they rarely if ever have unique solutions. Rather there are a series of alternative solutions all of which may be ranked on some value scale. Unfortunately for the problem solver, the value scales are subject to variation due to the conflicts of interests involved in the problem. The task of the consultant, technologist, problematist or whatever is not so much to find the "best" alternative, but rather the more difficult task of finding a viable alternative. This is an alternative to be agreed to by all parties involved in the solution of the problem. Intuitively the most viable alternative would involve the least number of compromises.

"Surely" - thought Amory - "this is a case of utmost simplicity. The structure failed due to under-design or due to some operating oversight. How else can structures fail?"

Still the nagging thought of those longitudinal cracks kept worrying him.

PUZZLER NO. 1 :

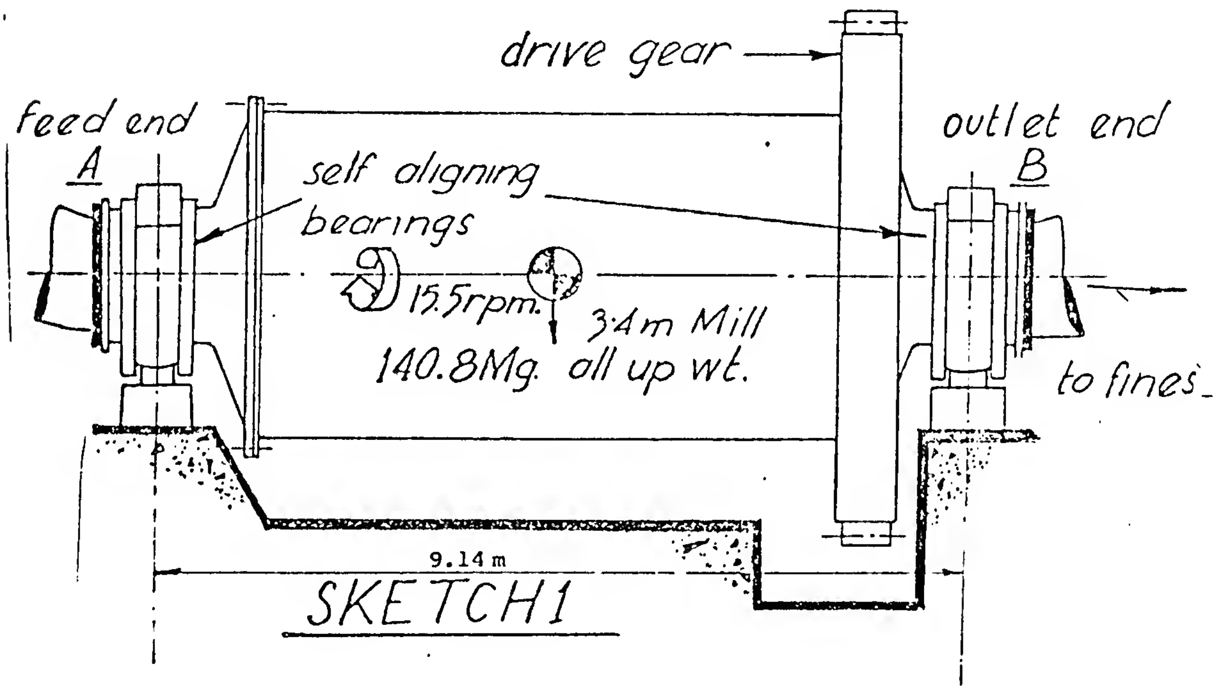
What is it about longitudinal cracks that is disturbing Amory? (Straight answers only, please)

Write out a checklist suitable for the interview during the two-hour trip to the TRUGRIT plant. Your checklist should contain all the background questions necessary to "put you in the picture", as well as questions raised in your mind by the information given so far. Please remember that your questions should not raise doubts about your competence in the mind of Grearson.

2. THE QUARRY AT CLOSE QUARTERS (Thursday, 21st Oct.)

Notes from an interview with Jim Grearson Australian sales manager for TRUGRIT. (The material has been transcribed, with only minor alternations, from the notes taken on the journey to the Geelong plant of TRUGRIT).

Amory(AA) : Correct me if I am wrong, but as far as I understand your operations look something like this: - (Refer Sketch 1)



SKETCH 1

1. Your mill is a conventional ball mill used for crushing raw feed, a material high in various clays such as broken bricks and quarried clay rocks.

2. The raw feed is fed in at the trunnion A, called the "feed end" and the feed is recirculated through the mill for another go.

3. Hot gases are also supplied at the feed end to dry the make-up feed for easier crushing.

Grearson (JG) : Your outline puts the operation in a nutshell.

AA : Could you outline some of the plant history?

JG : The plant was built by WHACKO Constructors, a small engineering firm under contract to SLIK Builders. On completion of the contract SLIK were going to operate the plant on a freelance basis taking peak load orders from the major cement companies. At the end of '66 the Melbourne building boom bottomed and SLIK's agreements with the major cement companies began to show signs of severe strain. In order to prevent catastrophic failure SLIK pronounced themselves bankrupt and subsided from the scene. WHACKO bridged their financial gap by selling the part-completed plant to the highest bidder, TRUGRIT.

AA : Weren't you taking a chance in buying a plant like that?

JG : Yes we were. It was not built to our specifications and didn't carry the usual guarantees, but we went into the deal with our eyes open. The bid we made was considerably less than what we would normally pay for such a plant. Given reasonable business recovery we would certainly recoup any losses we may incur due to excessive maintenance costs.

AA : What about now? This failure is more serious than you would expect under the heading of excessive maintenance costs.

JG : Certainly. You need to find the fault before we decide where to lay the blame. It's too early to be introspective.

AA : How long has the mill been operating since commissioning?

JG : About eight years.

AA : Continuously?

JG : Yes, apart from turn-around maintenance. We seem to have very little trouble with equipment.

AA : What about your operations? Are they fairly standard? Do other cement makers do much the same sort of things you do in producing cement?

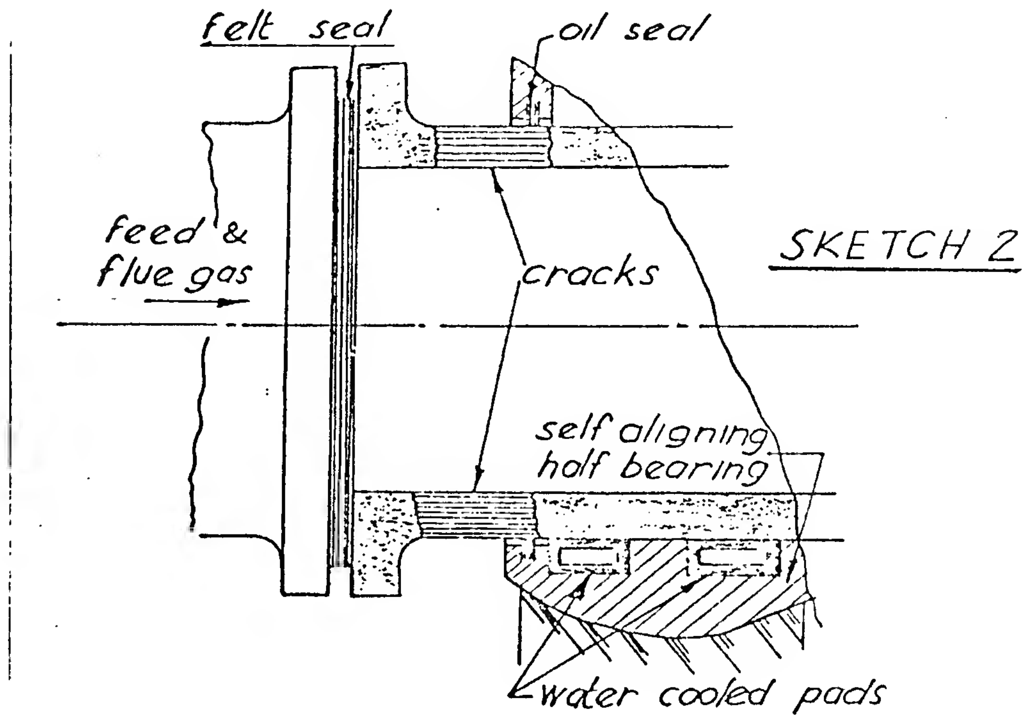
JG : Yes. Can't think of any major differences.

AA : How was the failure discovered?

JG : The ball mill runs in two water-cooled plain journal half-bearings. The bearings are oiled at regular intervals about twice a week I think. About a month ago the maintenance oiler noted some dust marks on the trunnion at the feed end. Thinking that they got there from external sources he wiped them off. When he noted the dust marks again in the same spot two days later,- he became suspicious and raised the alarm.

The mill engineer inspected the trunnion and called SONIC Engineering, a consultant in non-destructive testing. Their report showed two cracks diametrically opposite each other and running from the inlet flange to the point just inside the bearing cover (approximately 250mm). Both cracks are parallel to the axis of rotation.

AA: Something like this?



JG : More or less true. Some of the details of your sketch will need to be filled in, but Noel Williams the engineer at our plant will give you any information you may have missed.

Amory sat back puzzled. "After eight years of satisfactory operation a component fails. There are neither any operational abnormalities, nor any revolutionary design features involved. Yet somehow something about the whole thing seemed decidedly odd. What was it? Did they suddenly overload the trunnion or was it a gradual fatigue type of failure?"

Then he suddenly saw it. Astonishing as it was, he just now noticed that the failure had occurred where there was no apparent structural load on the trunnion.

3. THE TIGHT SHIP (The same day)

"We run a tight ship here" offered Harry Tomlinson the plant manager at TRUGRIT, Geelong, after the prefunctory introductions were completed. "In many ways our plant runs along the lines of a chemical process plant", he continued. "The operation is almost automatic and we monitor process conditions at all critical points in the plant".

"There are interlock cutouts in case conditions vary outside preset limits", cut in Noel Williams rejecting the backstage role bestowed on him during the introduction proceedings.

Tomlinson, a small dapper man in his early fifties, was introduced to Amory on his arrival at the plant. A man with a grammar school background, including some training in business economics and finance, was Amory's first estimate. This estimate was further reinforced during later discussions. Tomlinson had been with the plant for all of its operating life as manager. He knew all about cement-making operations, but talk about component stresses or plant safety had him floundering. He managed to convey one rather curious piece of information to the growing puzzle of the failure.

"This raw mill is a dry processing mill" was his almost terse introductory remark relating to the failure. He continued "other mills use a wet grinding process, which is slower than ours as well as inherently more expensive due to the higher capital cost involved in the plant. There are several stages of the wet process and the material flow is vertical involving a tall supporting structure. Furthermore, wet grinding is not a continuous process like ours" he concluded.

Amory was again puzzled, "I had the impression that dry milling is the normal method for producing raw feed", he offered. "No doubt the result of a misspent youth", he tried to soften the blow of this relevation of ignorance.

"Oh no", said Tomlinson. "In fact there are only two or three of this type in Australia, all of them in our cement plants".

"Had any strange experiences with the other mills lately?" questioned Amory.

"None that I know of", came the answer.

Williams the plant engineer rose from the ranks during the operational period of the cement plant. He was brought in as a maintenance fitter in the early stages, when it was thought that the plant needed only a skeleton operating and maintenance staff. To his credit was the fact that he took little time in catching up on maintenance planning and instituting preventative maintenance schedules and instruction manuals at the plant.

Failures in the plant tended to evolve rather than happen. Most of the atmosphere was corrosive or highly abrasive. As plant engineer he tried to keep abreast of recent developments in materials and processes to overcome plant problems in the long term. Williams supplied the drawings of the failed trunnion and the supporting half bearings for Amory to inspect. During this inspection Amory questioned him on his experiences with the operation of the plant.

"What is your version of the history of the mill?"

"Well", said Williams, thoughtful, "it was already operating when I came on the scene. Later on I found out that the trunnion was cast and machined by Wicked Ltd. There were three trunnions cast, one for each end of the mill and one spare. As with all these large castings under structural load we (TRUGRIT) specify full x-ray inspection. Fortunately this part of the plant was still in the construction stage when TRUGRIT took over and they got the inspection done".

"Were any flaws revealed in the inspection report?" pressed Amory.

"Only surface flaws", continued Williams. "These were plugged, but the spare casting is so full of surface flaws it would cost almost as much to repair as it would to cast a new one".

"In any case", he offered, "we can't take the chance of simply replacing the trunnion until we know what caused the failure. We may need to modify the design."

The "design" as Amory was to find out later, was deceptively simple (Refer Exhibit A). The trunnion, a cylindrical casting approximately 1.4 m outside diameter and 56mm wall thickness had a 1.6 m flange at one end and the other

end funnelled out to a 3.8m diameter flange. The bearings were self-aligning half bearings with plain water-cooled pads. Amory observed the thermocouples embedded in the water-cooled pads.

"What are these set on?" he asked.

"We run them around 60 - 65° C, but the cutout is set at 80° C," replied Williams.

"What do the makers specify for this type of bearing?" Amory probed.

"80° C maximum", said Williams, "but we don't like to operate near this level. Melted bearings tend to be a nuisance not only because of lost production, but they are also hard to replace."

With the preliminary questioning over the party of Grearson, Tomlinson and Williams were to take Amory on an inspection tour of the plant, but Williams excused himself on grounds of "pressing business in the plant".

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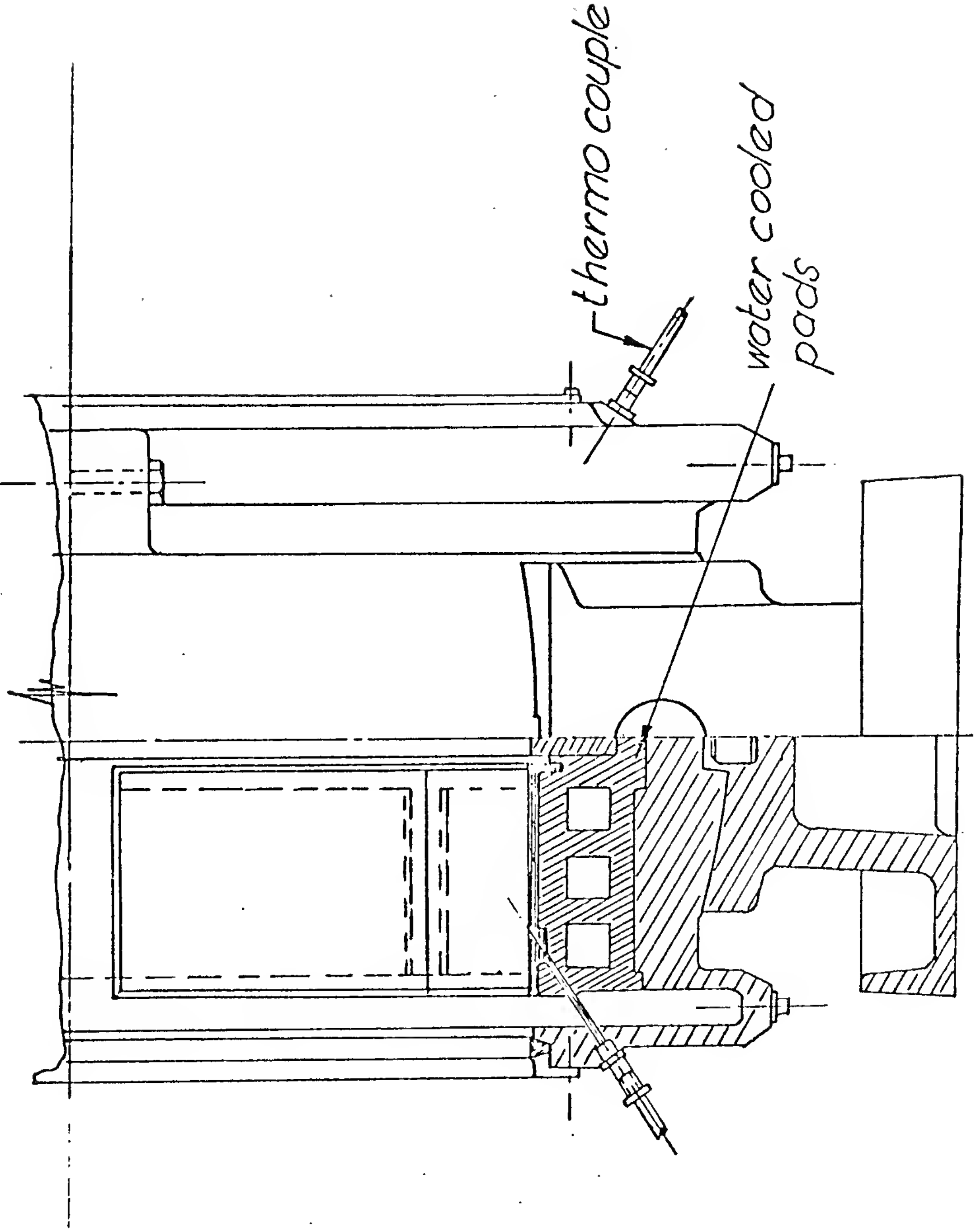
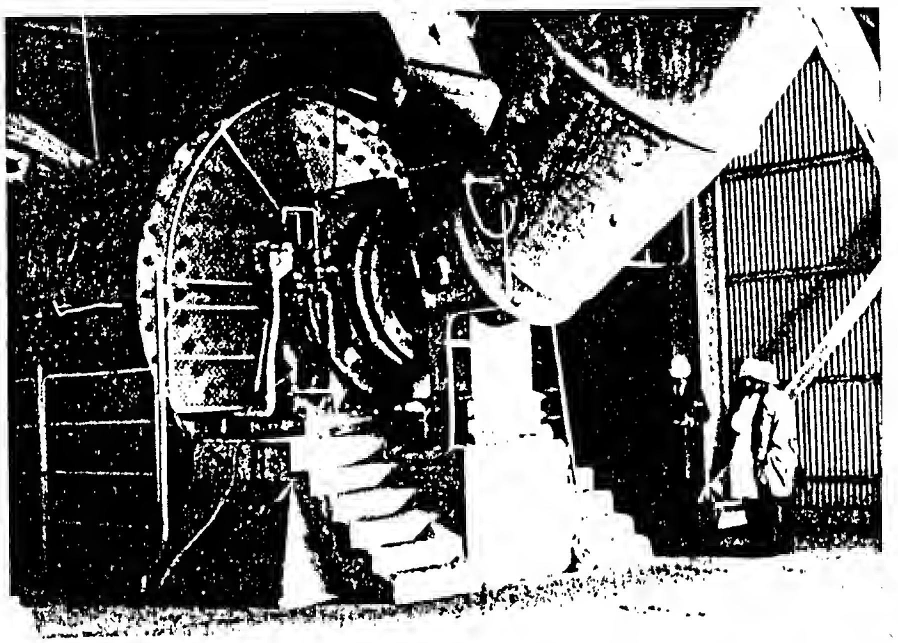


Exhibit B.

Section of self-aligning half bearing.



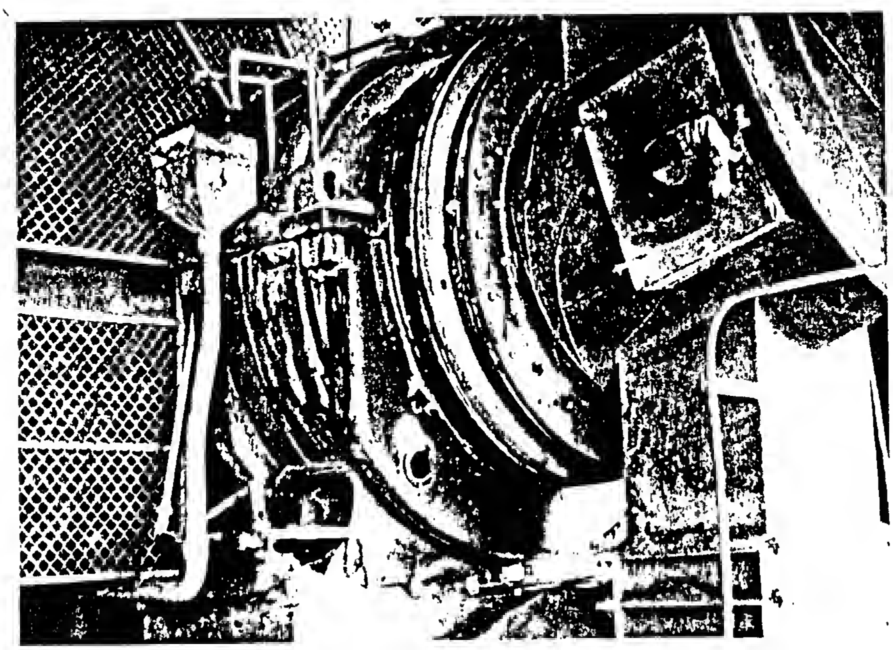
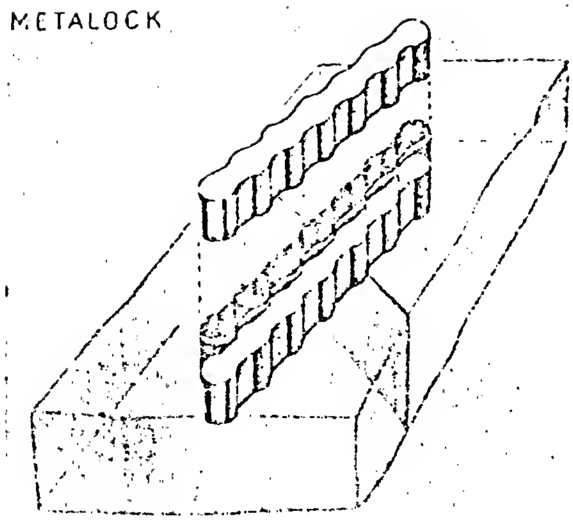


Exhibit C.

General view of mill and close-up of bearing.

METALOCK



METALOCK is the trade name for specially formed keys made of special alloys. Slots are cut transverse to the fracture and METALOCK keys are inlaid by cold working into the parent metal. The alloys having a known tensile strength and the serrations of the keys having a known shear strength, a precise amount of strength is restored as each key is inserted.

Figure 1 shows stress distribution as developed in photo-elastic studies of METALOCK repairs. Although it is impossible to duplicate an actual repair in plastic, we may conclude that pre-stressing of the parent metal takes place as indicated. Such prestressing is of benefit in repairing castings subject to heat and pressure.

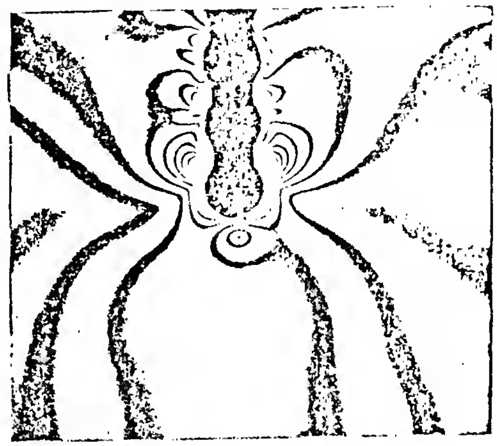


Figure I.

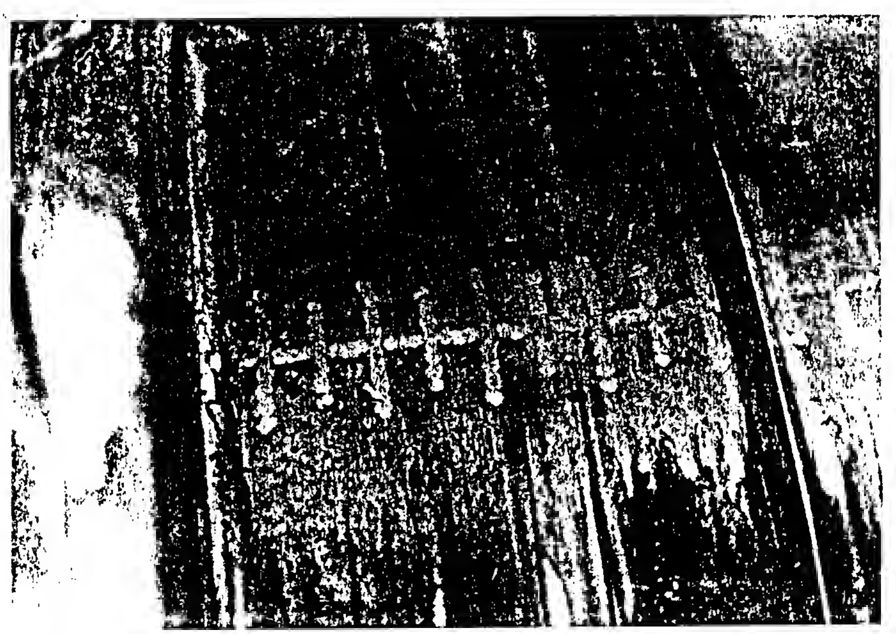


Exhibit D.

Description of Metalocking process and photo of Metalocked crack.

4. A KNOTTY PROBLEM (The same day)

Having returned to his office Amory assembled all the information he has collected so far.

1. The mill rotates at 15.5 rpm, and has an all-up weight of 140.8 t .
2. The material used in the trunnion casting was a 0.35% carbon steel with trace element additives to enhance castability and machinability. The metallurgical report supplied by Wicked, the manufacturers of the trunnion casting, read :-

Yield Strength	262 MPa
UTS in tension	572 MPa
Youngs Modulus	210 GPa
Poisson's Ratio	0.25

3. The mill has operated successfully for a period of about eight years. Neither during this operating period nor during construction have there been any apparent causes, changes in operating conditions or loads to offer clues to the causes of subsequent failure.
4. The failure has occurred in the feed end trunnion, which is identical in shape and constructional detail to the outlet trunnion. There are some loading differences between the two trunnions. These loading differences are due to the mill drive (a 4.5 m drive gear is placed near the outlet end of the mill) and are such as to load the outlet end more than the inlet end.
5. The two support bearings are identical.
6. The failure resulted in two longitudinal cracks about 250mm long on approximately diametrically opposite end of the feed end trunnion.

Points 1 to 6 above represent the major set of facts concerned with the failure. As well as these Amory, an observant investigator, stored away what he regarded as interesting though not necessarily relevant facts he referred to as "subsidiary information".

7. Dry milling is not as widespread as TRUGRIT sales manager, Grearson would have you believe.
8. The plant as a whole was acquired on a "turnkey" basis with none of the usual guarantees.

9. Trunnion bearings are operated nearly 20°C below the recommended maximum temperature by the makers.

10. Cost of a new trunnion would run to about $40,000.

Naturally it became clear that some deductions may be formed immediately on the basis of these facts. Furthermore various forms of failure hypotheses may be formulated.

First, the deductions :-

(a) Since there are no significant structural loading differences between the inlet end and the outlet end, the failure must have been caused by something operational and peculiar to the inlet end.

(b) Since the failure occurred after a prolonged period of satisfactory operation, the possibility of some type of fatigue failure needs to be considered.

(c) Whatever caused the failure must have caused excessive hoop stress in the trunnion since the failure cracks are parallel to the axis of rotation (longitudinal).

Secondly, Amory set about proposing a suitable hypothesis for the mode of failure. He wrote :-

Hypothesis : Fatigue failure due to some form of structural loading. Enlarging on this line of thought Amory continued -

Since the mill runs in half bearings and these impose only minimal restraint to deformation, the mill and the trunnions may be regarded as a simply supported structure. Under this assumption the point of failure represents a point of almost zero structural load. Consequently there are two alternative causes of failure under this hypothesis.

(a) Excessive flexing of the trunnion due to structural deformation caused as a result of elastic distortion of the whole structure, or limited structural distortion of the feed end bearing or a combination of both.

This flexing or distortion would need to be of a "tube flexing" type to produce the observed hoop stress condition. Stress cycling could lead to eventual failure.

(b) Excessive flexing or distortion of the trunnion due to thermal effects. These effects may be random but of sufficient severity and quantity to eventually fail the trunnion.

With his facts assembled Amory cast himself in the role of engineering detective and planned his next move with care. He felt he should not spend undue effort in any structural or thermal analysis. Surely this was not warranted by the problem. The mill designers, an internationally known and reputable firm, would have done all the necessary calculations during the design stage, "Or was this a rash assumption?" he questioned himself.

"Perhaps", he said to himself, "by simple order of magnitude arguments he could eliminate all but the most viable alternative".

Still deep in thought he rang the mill :-

"Hallo Noel", he greeted Williams when the engineer came on the line, "how is your crack propagating?"

"No change, but how are your academic prognostications coming along?", came the mildly derisive rejoinder.

"It's the work of the trunnion fairies", conjectured Amory tongue in cheek, "you know they are opposed to raw feed milling in this country". He continued, "before I can write up my report on trunnion fairies I need some details of the trunnion liner shown on your drawing".

"Well", drawled Williams, "the mixing paddles shown on your copy of the drawing were removed early in our operating history, but I can let you have a sketch of the modified liner".

"Why the change?", questioned Amory.

"Ah well", came the laconic reply, "when we first started up we had a slight overheat problem on the feed end. Eventually we melted a bearing pad and that was when we designed the liner. It was also at that time I got the operating boys to reset the bearing temperature level by increasing the cooling rate", he concluded.

"Has all been well with the running temperatures since the change?", questioned Amory.

"No problems until the cracks. In fact at last turn-around we removed the new inner liner just to see what would happen".

"Well?", asked Amory.

"Same as before", answered Williams, "only this time we kept our eye on it and the bearing didn't melt. Naturally we put back the new liner shortly afterwards".

"O.K.", said Amory, "send me a sketch of the new liner thanks Noel". He continued, "I'll come down on Thursday next, can you stop the mill for a quarter of an hour or so?"

"No problems, look forward to seeing you", rang off Williams.

Amory didn't know whether to feel pleased or annoyed. Why the hell didn't they tell him about this liner business at the mill? Was it the presence of "big boss" Grearson he wondered, or was it plain negligence? Surely they couldn't think it too unimportant to mention?

PUZZLER NO. 2 :

What should Amory conclude from the information so far given?
Write a short checklist of things he should ask and do at the plant on his second visit.

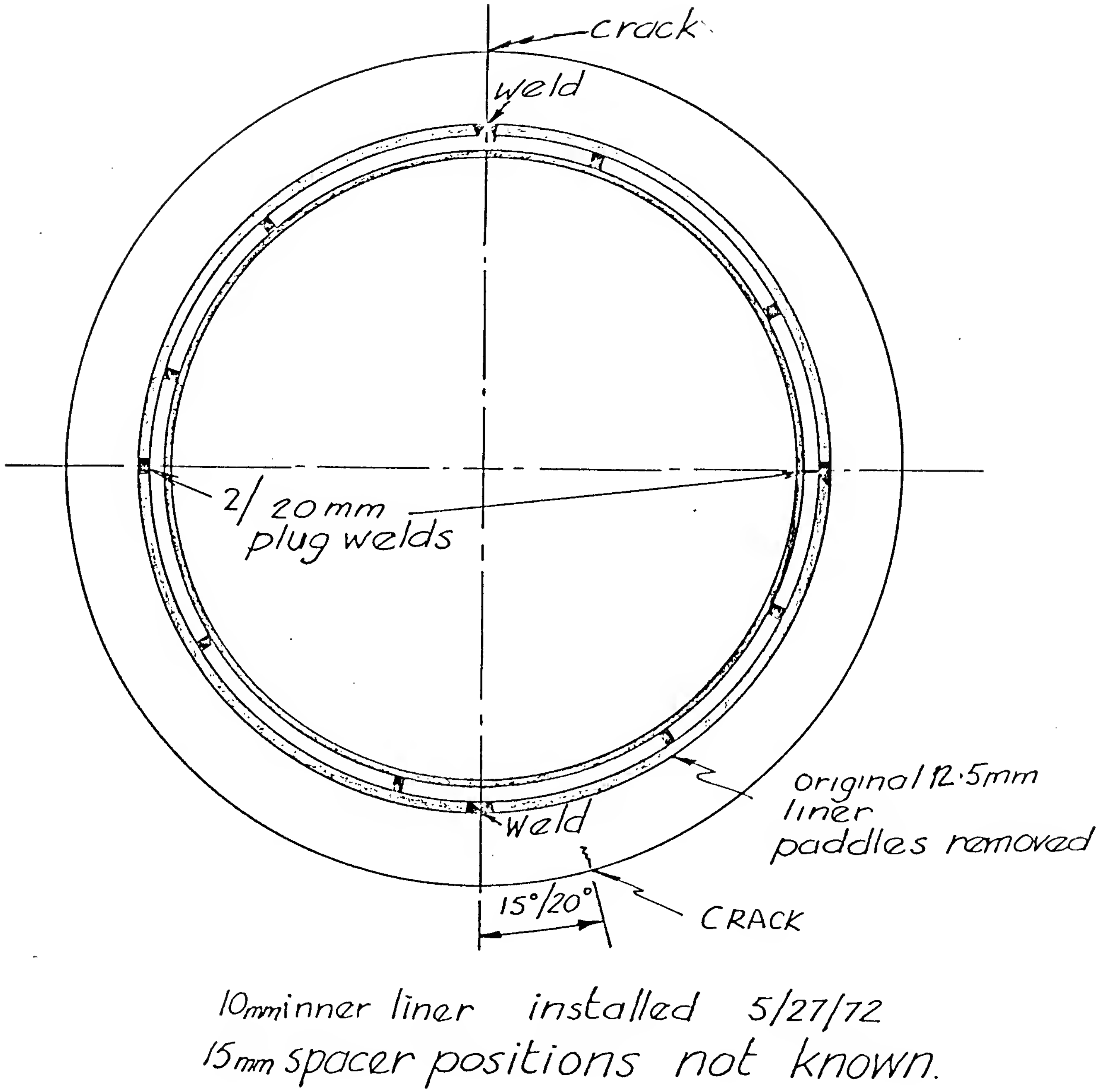


Exhibit E.

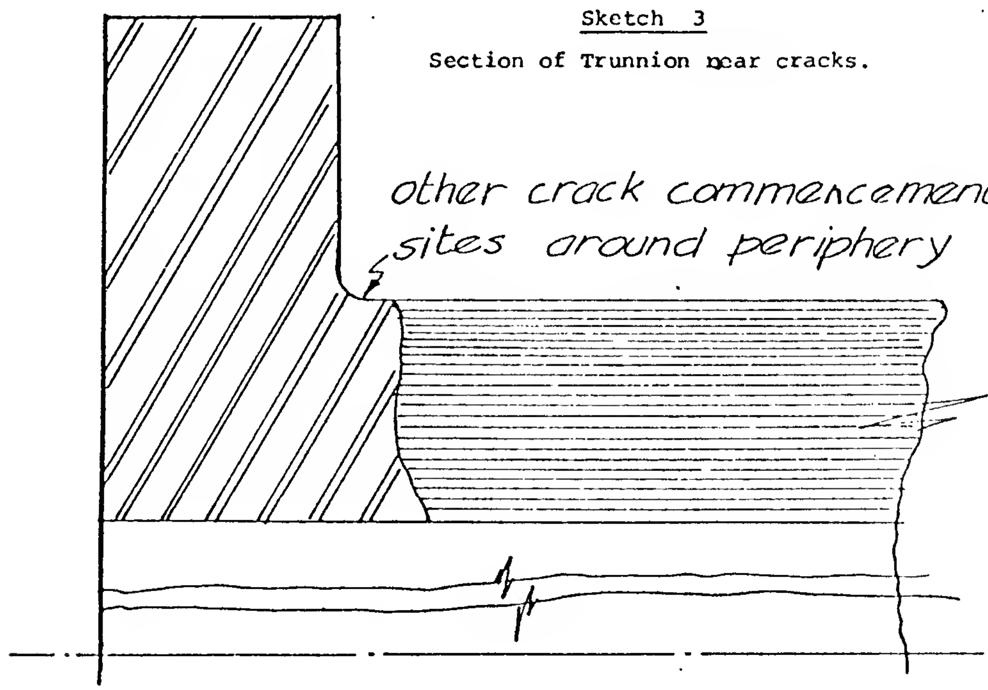
Raw Mill Feed End Trunnion - Location of Cracks and Liner Welding.

5. ANALYSIS OF THE PROBLEM (During the next week)

A few simple calculations further confirmed Amory in his initial sizing up of the problem. The hoop stress, caused by even the conservatively large structural loads assumed to act on the inlet end of the trunnion he found to be negligible. Nevertheless Amory went to considerable trouble to eliminate from consideration structural stresses as possible causes of failure. He reasoned that if structural loads were involved in the failure there should be some evidence of other hairline fatigue cracks on the trunnion apart from the two major cracks under investigation. He figured that the base of the feed end flange would represent a likely source of stress concentration associated with some kind of complex trunnion-flange twisting or bending process. There seemed no obvious reason for the major cracks occurring where they did and a random process would have produced other crack commencement sites as well. For these reasons Amory planned to take some penetrant dye to check out the trunnion on his next visit to the plant.

Sketch 3

Section of Trunnion near cracks.



Next Amory tackled the thermal analysis in two parts, namely :-

(a) tangential or "hoop" stresses due to differential thermal expansion between the trunnion and its liner, and

(b) tangential or "hoop" stresses induced by thermal gradients in the trunnion.

The analysis of the differential thermal expansions was simplified by some crude but expedient assumptions. The results showed stress levels more significant than those due to structural loading, but still too low to cause failure. Analysis of the effects of thermal gradients required some information about the working temperature gradients in the trunnion. A further telephone call to the mill revealed that there were no records of trunnion temperature at the mill. Amory had to face the task of taking surface temperature measurements at the mill. He didn't relish the idea of taking such measurements while the mill was stationary, because he was more interested in steady state conditions than some exotic transient situation. A few telephone calls to instrument firms gave him the solution to the problem in the form of small magnetic surface thermometers. These could be attached to the mill trunnion and the dials could be read while the mill was revolving. After all 15.5 r.p.m. didn't present too great a challenge.

6. SECOND FIELD EXCURSION (Thursday, 28th Oct.)

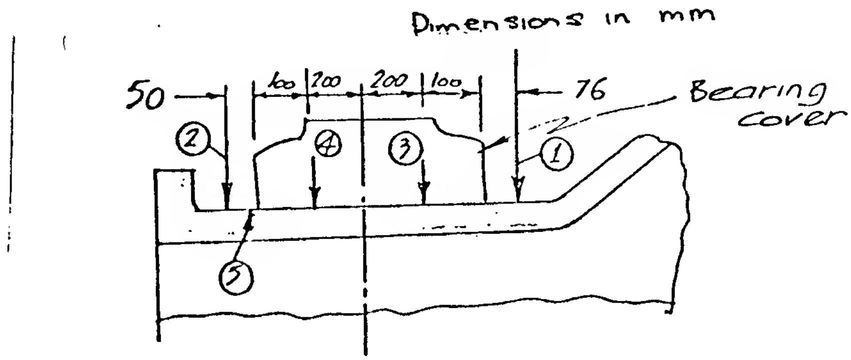
At the mill Amory used a spray-pack penetrant dye on the trunnion, covering as far as possible all of the area accessible outside the bearing housing. After application the surface of the trunnion was cleaned, sprayed with developer and examined under ultra-violet light. The dye would fluoresce under the ultra-violet and cracks not visible to the naked eye could be observed since the developer tends to leach the dye from the crack onto the surface just adjacent to the crack. Amory's efforts in crack detection were fruitless. Inspite of all his efforts Amory found no trace of any other crack commencement sites on the trunnion. However, his efforts in temperature measurements were more rewarding. He took three sets of measurements including two sets of steady state temperature readings while the mill was running and one set of transient readings while the mill was stopped for a period of five minutes.

During the time the mill was stopped Amory observed a 10° to 12° C. rise in temperature at the inlet end of the trunnion. His curiosity aroused, he visited the control room to find that the flue gas inlet temperature to the mill was recorded continuously. The records showed that the gas temperatures can rise to a high of 450°C. in a very short time on a scale of minutes. Further investigation showed that the flue gas comes from a kiln just upstream of the mill. Since the kiln cannot be shut down simultaneously with the mill, the sequence of operations during a mill shut-down is critical. Even when the mill is running, feed blockages can occur. The flue gas is used to dry the feed and in a sense the feed provides a kind of evaporative cooling of the flue gas. If the flue gas is not allowed to bypass the mill during shut-downs or feed blockages, then inlet gas temperatures will soar to very high values. In the mill operation the bypassing process was found to be a manual operation. Since the feed stoppage is a random event, inlet temperature rises can and do occur depending on the alertness of the operating

crew. Amory's results of temperature measurement are set out on Exhibit F .

PUZZLER NO. 3 :

How would you analyse the trunnion given the temperature data in Exhibit F ?



Schematic of Temperature Recording Stations

Test No. 1 (3.15 pm)

T1 = 78

T2 = 107

Test No. 3 (4 pm)

T2 = 90

Test No. 2

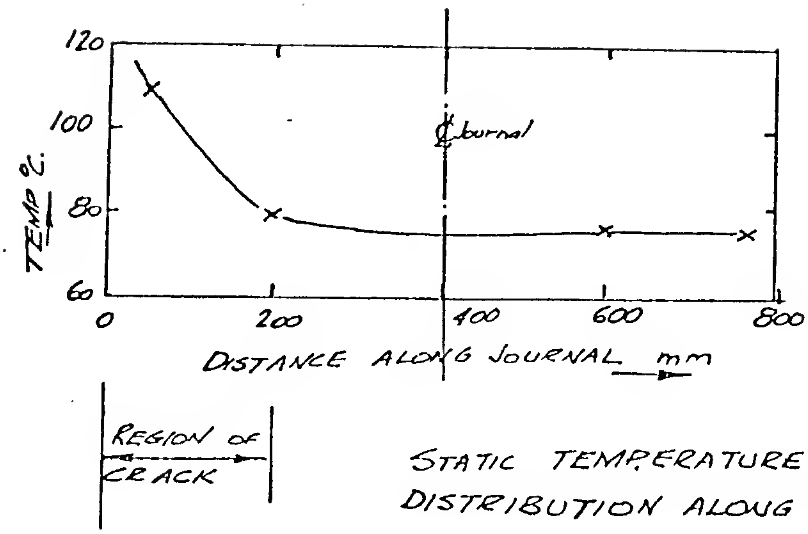
Time	T3	T4	T5
3.36	61	66	73
3.37	66	72	77
3.38	66.5	75	77
3.39	67	76	78
3.40	70	77	79

Mill Gauges

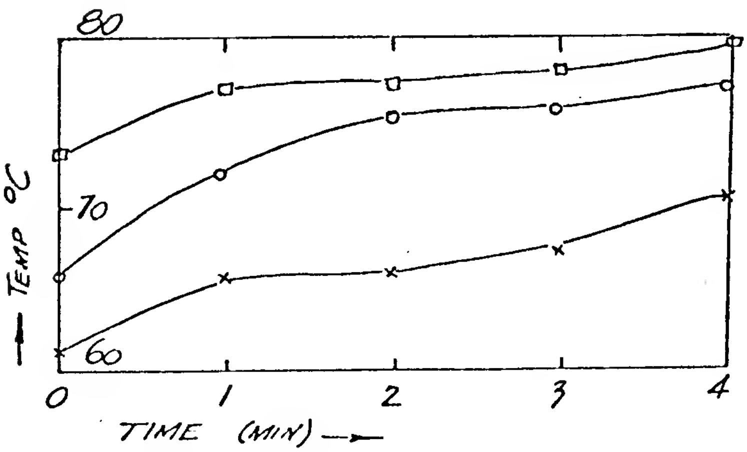
Upstream	63
Downstream	64

NOTE : All temperature measurements in °Centigrade and the mean of several readings is given.

Exhibit F - Temperature Measurement Data.



STATIC TEMPERATURE DISTRIBUTION ALONG JOURNAL



TRANSIENT TEMPERATURE DISTRIBUTION

Exhibit F. (cont'd)

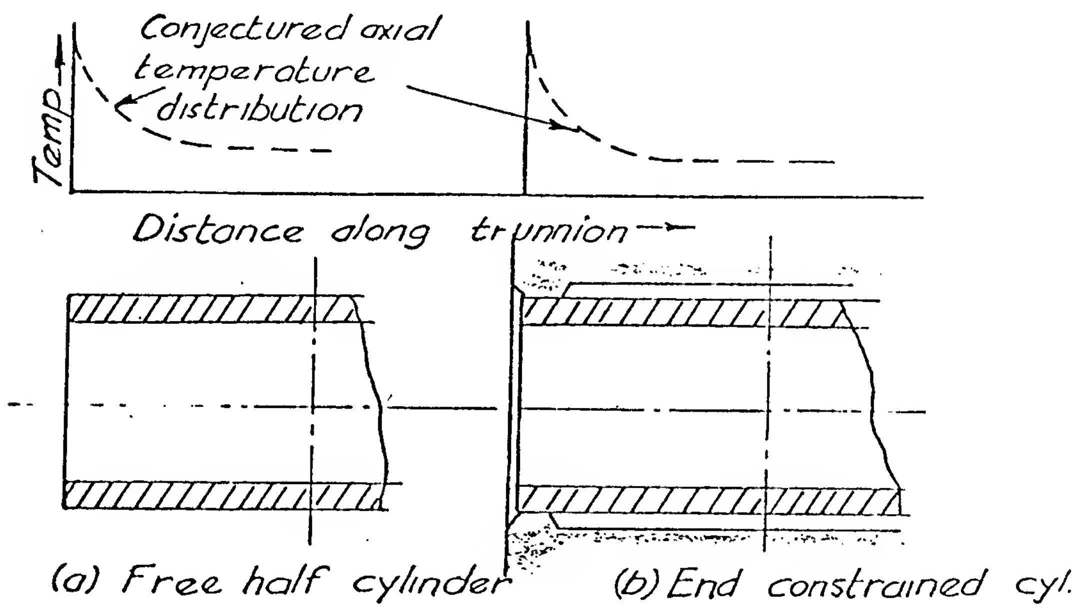
Temperature distribution in trunnion.

7. CONCLUSION

In making his estimate of stresses due to thermal gradients Amory found a reference* which treated the behaviour of thin cylinders under thermal effects. He considered two cases, namely :-

(a) Free half cylinder with axial temperature distribution, and

(b) a cylinder with constrained ends also with axial temperature distribution.



Sketch 4 - Trunnion Models Analysed.

He reasoned that the flange at the outer end of the trunnion would impose a strong constraint to deformation and he hoped that (b) above, would account for this case. Details of the calculations for both structural as well as thermal effects are given in the Appendix. The results of these calculations showed that hoop stress levels in the trunnion could exceed the material yield strength when the gas temperature at the inlet exceeded 400°C. Amory felt relief when his calculations finally began to show significant stress levels. He felt he had isolated the real culprit in this case. He also felt

*Kent, C.H. - "Thermal Stresses in Thin Walled Cylinders" Transactions of the American Society of Mechanical Engineers, June 1931.

reasonably certain that this aspect of plant operation has escaped the attention of plant designer and plant operator alike. Little did he realise however the "can of worms" he opened up when he presented his conclusions in a preliminary report to Australian Sparrow Insurance.

Department of
Mechanical Engineering
Melton University
Parkville Road, Claytrobe,
Vic. 3111.

4th November 1976.

Mr. Adam Jones,
Plant Actuarian
Australian Sparrow Insurance Co.,
134 Burkston Street,
Melbourne, 3000.

Dear Mr. Jones,

Subject: TRUGRIT Cement Mill Failure

I have examined all the facts of this case and my preliminary finding is that the failure was caused by thermal cycling of the trunnion under operating conditions which lead to inlet temperatures in excess of 400° C. Conditions were further aggravated by operating of the trunnion bearings at 20°C. below their recommended maximum.

The sites of failure are sufficiently close to the construction welds of the original trunnion liner to suggest that the welds are responsible for crack site initiation. This initiation process may have occurred due to a weakened metal structure or high stress due to improved metal to metal contact at the weld sites.

Several questions arise regarding possible long-term solutions to the problem. Perhaps the most important one is whether TRUGRIT can get away with a minor redesign or is a major redesign needed. The minor redesign of the trunnion liner was a step in the right direction, but this needs to be augmented by procedures at the mill to prevent inlet gas temperature rises above 350°C and bearing temperatures falling much below 80°C. The most significant means of preventing future failures lies in a major redesign of the feed inlet area. The attached sketch should provide one possible alternative approach. The calculations supporting my conclusions are also enclosed.

Yours sincerely,
Andrew Amory,
Senior Lecturer.

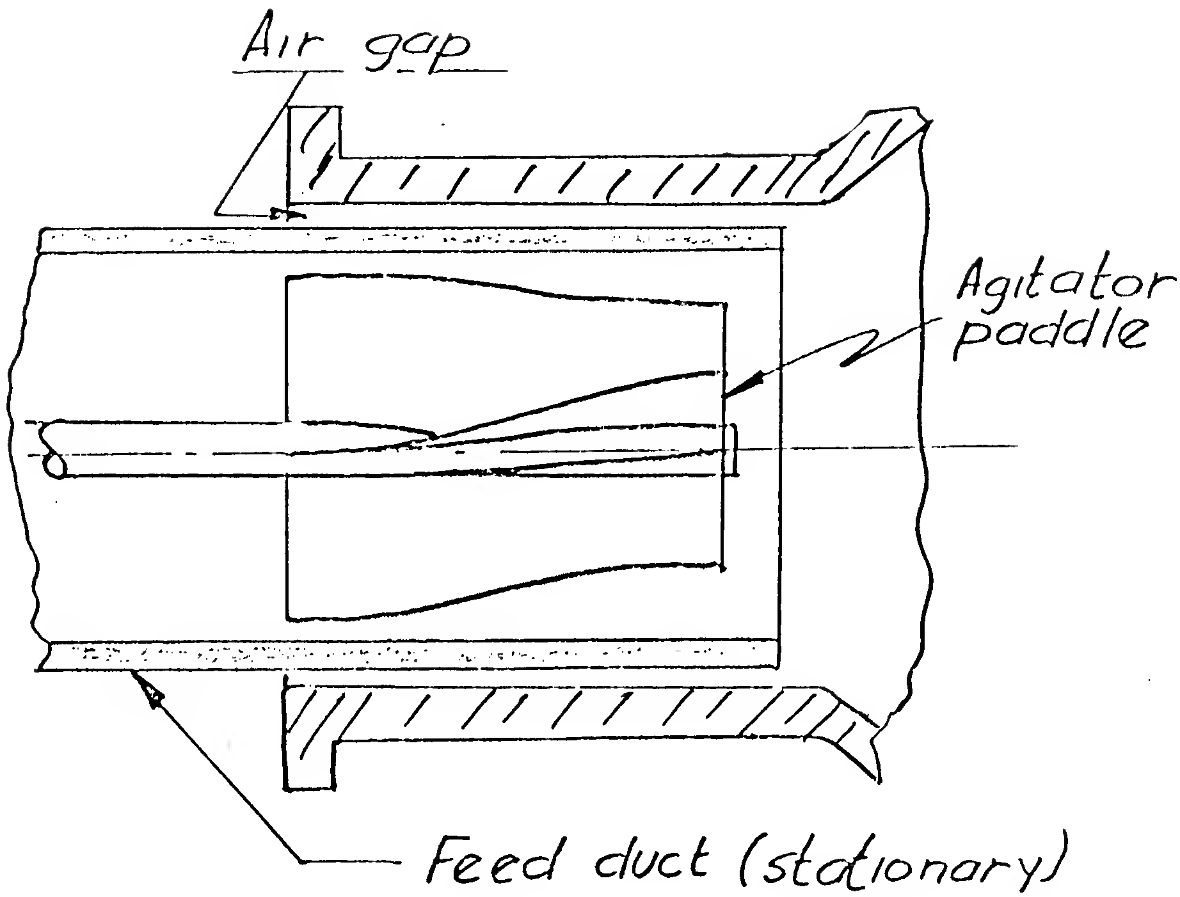


Exhibit G.

Suggested modification to the feed end. Feed and hot gases are introduced into the mill well beyond the cooled bearing area.

PUZZLER NO. 4 :

What problems do you foresee for the insurer in dealing with this case?

To ease your pains you should structure your answers under the following headings :-

(a) Should the insurer pay for the replacement trunnion or some part of it?

(b) Can the insurer recover some of his loss from the designer or the manufacturer of the mill?

(c) Should TRUGRIT sue the designer or constructor of the mill?

(d) Should the insurer ask for any sureties or guarantees, when covering this or any other mill (or any other equipment) for TRUGRIT?

8. THE CASE IS STILL OPEN (Wednesday, 17th Nov.)

The phone jangled Amory out of his Wednesday afternoon reverie.

"Saw your report", Grearson's voice sounded petulant, "are you sure about those figures?"

"As sure as one can be under the circumstances", offered Amory, puzzled, "but what seems to be the problem?"

"We have been in touch with Humbugs, the German designers of the mill, and they flatly refuse to accept your figures or diagnosis. What's more disheartening is that our principal, TRUGRIT U.K. Ltd., won't let me re-design the trunnion. They insist I keep running with the Metalocked trunnion and just keep monitoring conditions", finished Grearson sounding more tired than petulant now.

"Why can't you do the redesign under the counter?", prodded Amory, "you know what I mean, using local funds and local designers?"

"At my time of life", sighed Grearson, "I don't fancy looking for another job, even if I do believe your findings".

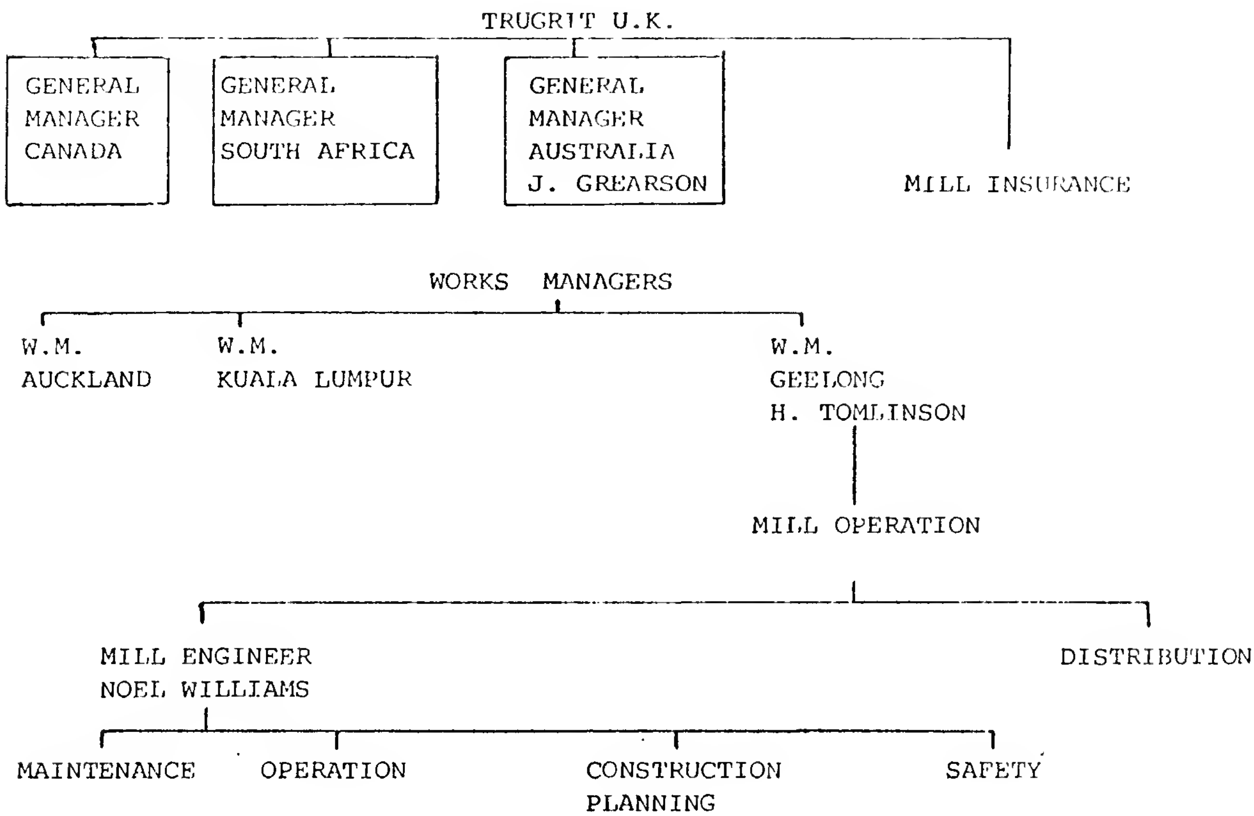
"Hope you can solve your people problems", said Amory, "but they are out of my domain".

After some further perfunctory niceties Grearson rang off and Amory sat musing about the whole picture. To get a view of the organisational interconnections in the case he drew up an organisation chart for TRUGRIT. He felt disappointed he didn't do this earlier. Had he done so he felt he may have produced a more viable alternative solution to a problem that with all his hindsight had a lot of "people content" quite apart from its technical difficulties.

To the best of the author's knowledge TRUGRIT is still operating with the broken trunnion.

EXHIBIT H

TRUGRIT ORGANIZATION CHART :



PUZZLER NO. 5 :

Comment on the case. Would you have handled the case differently? What if any action would you take after Grearson's call?

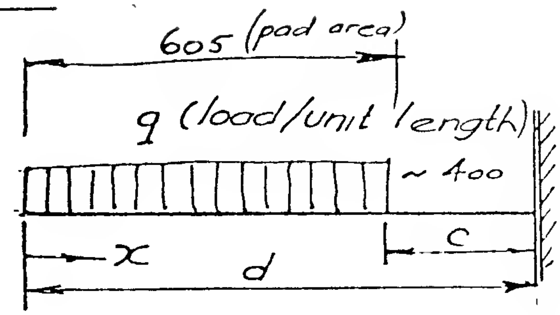
Do you agree with Armory's findings"

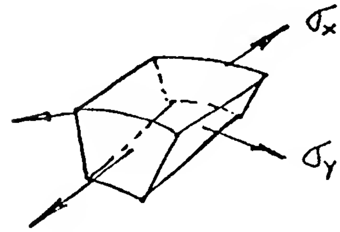
Do you have any alternative solutions for TRUGRIT? Detail these.

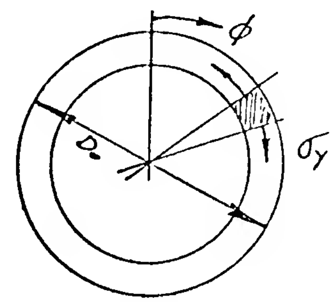
APPENDIX

A1

1. Stresses due to structural loads







Assume: selfaligning bearings do not "self-align"
trunnion is thin cylinder in bending.

Load $q = (140.8/2)/605 = 0.116 \; Mg/mm$

$M_x = qx^2/2 \quad \therefore \; \sigma_{x\,max} = M_x D_o / 2 I_{zz}$

$D_o = 1374 \; ; \; I_{zz} = \frac{\pi}{64}[D_o^4 - D_i^4] = 3.75 m^4 \times 10^{-2}$

$\sigma_{x\,max} = \frac{.116 \times 9.81 x^2}{2} \times \frac{1.374}{2 \times 3.75 \times 10^{-2}} = \underline{10.42 x^2 Pa.}$

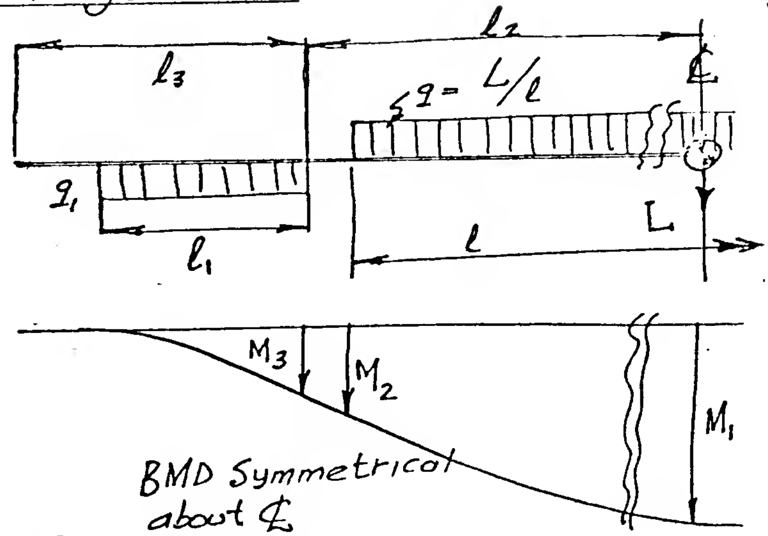
$\sigma_x = \sigma_{x\,max} \cos\phi$
$\sigma_y = \mu \sigma_x - \mu \sigma_{x\,max} \cos\phi$

for $\mu = 0.25$ at ¢ 1st bearing pad
$x \doteqdot .152 \, m$
$\rightarrow \sigma_y \approx \underline{6 \times 10^{-2} \, Pa.}$

<u>Negligible</u>

A2

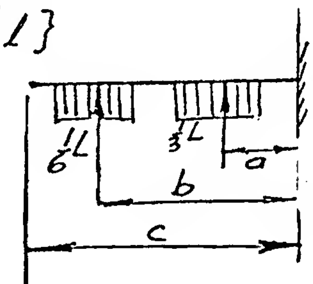
2 Deflection in journal



$M_1 = \frac{1}{2}L\{\frac{1}{2}l_1 + l_2 - \frac{1}{4}l\}$

$M_2 = \frac{1}{2}L\{\frac{1}{2}l_1 + l_2 - \frac{1}{2}l\}$

$M_3 = \frac{1}{2}L\{\frac{1}{2}l_1\}$



Assume load dist^n. as shown ie. $\frac{1}{3}$rd on outboard pad, $\frac{2}{3}$rd inboard.

Deflection $\delta_a = \frac{\frac{1}{6}L}{EI_{zz}}\left(\frac{ba^2}{2} - \frac{a^3}{6}\right) + \frac{L/3}{3EI_{zz}}a^3$

$\delta_b = \frac{L/6}{3EI_{zz}} \cdot b^3 + \frac{(L/3)a^2}{2EI_{zz}}\{b - \frac{1}{3}a\}$

with $E = 210$ GPa. ; $D_o = 1.374$ m

$I_{zz} = 3.75 \times 10^{-2} m^4$; $L = 140.8$ Mg.

$a = .64$ m
$b = .94$ m
$c = 1$ m

→ $\delta_a \doteqdot \underline{6.1 \times 10^{-3} \text{ mm}}$

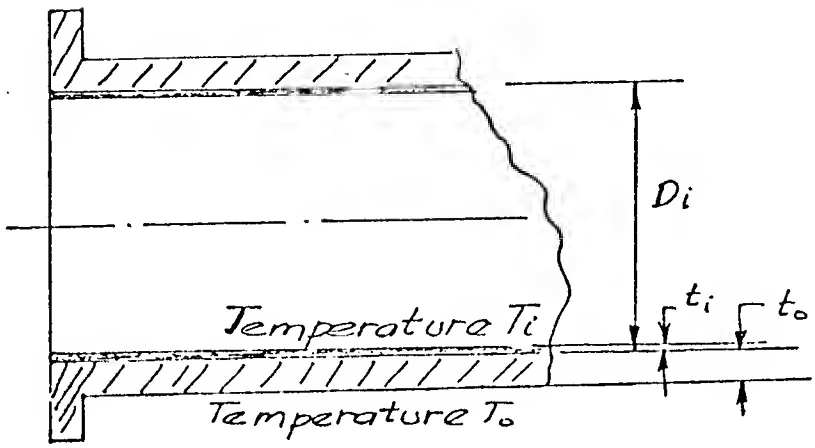
→ $\delta_b = \underline{8.9 \times 10^{-3} \text{ mm}}$ <u>Negligible</u>

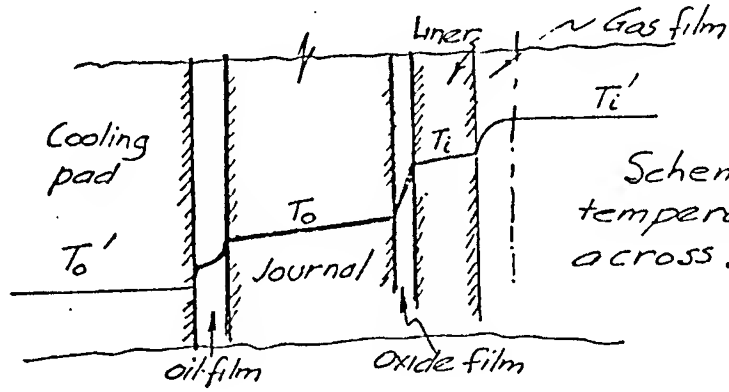
∴ Assume load evenly distributed along journal

A3

3. Differential expansion of Liner & Journal

3.1 original liner





Schematic of temperature dist^n across Journal & liner

Coefficient of thermal expansion $= \alpha/°C$

let pressure at interface be X Pa.

Hoop stress in outer shell $\sigma_{t_o} = \frac{X D_i}{2 t_o}$

——"—— inner ——"—— $\sigma_{t_i} = \frac{X D_i}{2 t_i}$

decrease in diameter of inner shell $= \sigma_{t_i}/E = \frac{\delta_i}{D_i}$

increase ——"—— outer ——"—— $= \sigma_{t_o}/E = \frac{\delta_o}{D_i}$

A4

$$\delta_i = X D_i^2 / (2 t_i E)$$

$$\delta_o = X D_i^2 / (2 t_o E)$$

Compatibility $\Rightarrow$ $\delta = \delta_i + \delta_o$, where

$$\delta = \alpha D_i (T_i - T_o)$$

$$\therefore X = \frac{2\alpha}{D_i} E (T_i - T_o) \left\{ \frac{t_i t_o}{t_i + t_o} \right\}$$

$$\therefore \sigma_{t_o} = \alpha E \overbrace{(T_i - T_o)}^{\Delta T} \left\{ \frac{t_i}{t_i + t_o} \right\} \quad *$$

α steel $= 11 \times 10^{-6} / °C$

$t_i = 12.5 mm$

$t_o = 56.5 mm$

$E = 210$ GPa

$\Rightarrow \sigma_{t_o} = 0.418 \Delta T$ MPa

3.2. MODIFIED LINER

(a) Assume t_i (effective) $= 10 + 12.5 = 22.5 mm$

$\Rightarrow \sigma_{t_o} = 0.658 \, \Delta T$ MPa

(b) treat original liner as part of outer shell ($t_o = 56.5 + 12.5 = 69 mm$); ($t_i = 10 mm$)

$\Rightarrow \sigma_{t_o} = 0.292 \Delta T$ MPa.

A5

4. Thermal stresses due to axial & radial temperature distribution.

CASE (a) FREE END

$t = 56.5$ mm ; $D_i = 1261$ mm

$\therefore \frac{2t}{D_i} = .09 < 0.1$ i.e. treat as thin cylinder.

Kent (1931) for $T = \frac{1}{2}\{A + B_0 x/l + B_1 x^2/l^2 + \cdots\}$ gives the maximum tangential stress in the cylinder with free end (model "a")

$$\sigma_{t_{max}} = \frac{E \alpha \Delta T}{2} (1.744) \text{ ; where}$$

E = Youngs Modulus (210 GPa)
α - Coefficient of thermal expansion
$= 11 \times 10^{-6}$ /°C
A, B_i are constants in a polynomial temperature distribution.
ΔT - max (radial) temperature difference

$$\Rightarrow \sigma_{t_{max}} = 2.014 \, \Delta T \text{ MPa.} \quad \text{— (4.1)}$$

CASE (b) Constrained end.

Using Kent's plots of stress σ_t

Free end $\sigma_{t_{max}}$ is reduced by 42.7% (reduction depends only on μ)

$$\Rightarrow \sigma_{t_{max}} = 0.608 \, \Delta T \text{ MPa.} \quad \text{— (4.2)}$$

A6

Case (c) Axial distribution of T assumed parabolic.

for this case Kent gives

$$\sigma_{t_{max}} = \frac{E\alpha T_1}{1.5} ;$$

where $T = T_1 (x/\ell)$ - distribution along trunnion mid plane.

$\Rightarrow$ for the trunnion

$$\sigma_{t_{max}} = 1.54\, T_1 \text{ MPa} \quad — \quad (4.3)$$

SUMMARY : from measured temperature distribution two cases emerge.

①: Inside temperature constant at some value near gas inlet T_i

$T_i = 270°C$ (say) $\Rightarrow T_1 \doteqdot 30$ (mean plane rise)
Near bearing $\Delta T \doteqdot 200$

②: Inside temperature drops to near bearing value ($\approx 80°C$)

$T_i = 270°C$ (say) $\Rightarrow T_1 \doteqdot 100$ (mean plane rise)
Near bearing $\Delta T \doteqdot 100$

① $\Rightarrow$ $\sigma_{t_{max}}$ = 402.8 MPa (4.1)
121.6 MPa (4.2)
46.2 MPa (4.3)

② $\Rightarrow$ $\sigma_{t_{max}}$ = 201.4 MPa (4.1)
60.8 MPa (4.2)
154 MPa (4.3)